RADC-TDR-63-283

April 1963

FOURTH QUARTERLY PROGRESS REPORT ON SOLID-STATE CIRCUITS

by

S. Hamilton, W. W. Heinz, S. Okwit, and E. W. Sard

AIRBORNE INSTRUMENTS LABORATORY
A DIVISION OF CULTER-HAMMER, INC.
Deer Park, Long Island, New York

REPORT NO. 1654-I-4

Contract AF 30(602)-2699

Prepared for

Rome Air Development Center
Research and Technology Division
Air Force Systems Command
United States Air Force

Griffiss Air Force Base
New York

NOTICES

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ABSTRACT

Calculations of the expected performance of the unmatched Bendix circulator, as predicted by Bosma's analysis, were completed. Experimental data was obtained using the proper center conductor that agreed qualitatively with the theory. A study was made of the effect of center-conductor shape on the desired circulator matching locus. A junction having a filleted shape was found to yield the most desirable locus. This center conductor, with the addition of quarter-wave transformers and tuning screws, gave a circulator with 20-db isolation from 3.75 Gc to 7.3 Gc and an insertion loss of less than 0.5 db.

The qualitative study of idealized input impedance of a parametric amplifier, performed during the early phases of this program, was used to double-tune the balanced C-band parametric amplifier so that the phase shift would be a linear function of frequency. This technique was very successful, providing a 500-Mc instantaneous bandwidth with a gain of about 10 db, a noise figure of 3.55 db, and a relatively flat phase characteristic. The amplifier has been packaged in a standard 19 by 24 inch rack mount, and is completely self-contained.

Title of Report RADC-TDR-63-283

PUBLICATION REVIEW

This report has been reviewed and is approved.

Approved: Paul H. Baldwin
for Lt Col USAF
ARTHUR J. FROHLICH
Chief, Techniques Laboratory
Directorate of Aerospace Surveillance & Control

Approved: Paul H. Baldwin
for Lt Col USAF
WILLIAM T. POPE
Acting Director
Director of Aerospace
Surveillance & Control

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I. INTRODUCTION

Airborne Instruments Laboratory (AIL) is required to study, design, and develop:

1. Low-level solid-state limiters covering the 400 to 800 Mc range,
2. Three-port circulator covering the 4 to 8 Gc range,
3. Low-noise solid-state C-band amplifiers suitable for use in pulse-compression radar systems.

The effort on the first task (low-level limiters) was completed during the previous report period with the successful operation of a low-level varactor limiter having a threshold below -20 dbm and an ultradynamic range of 70 db.

Of the total funds allotted for this program, about 85 percent have been expended. The progress of the work to date is as scheduled, and the program will be concluded within the allotted funds.

A list of the key personnel assigned to this program are:

S. Hamilton

W. W. Heinz

S. Okwit

E. W. Sard

II. 4 TO 8 GC CIRCULATOR

The purpose of this task was to develop a design theory for a strip-transmission-line Y-junction broad-band circulator, and to design and construct two breadboard models of a fixed-tuned circulator covering the 4 to 8 Gc range.

Calculations were made of the performance of an unmatched Bendix circulator as predicted by Bosma's analysis. Performance with the proper center conductor agreed qualitatively with predicted performance.

A strip-transmission-line slotted section was constructed to measure the transition between the line and the coaxial connector in the Bendix circulator, and to measure reflection coefficient loci of actual matching networks. Preliminary results show that a poor transition exists, which could account for the partial success in experimentally matching the circulators over a wide band.

A study was made of the effect of the center conductor shape on the required matching locus. A junction having a filleted shape was found to give the most desirable locus. As a supplementary means of obtaining a match over a wide band, tuning screws were used along with quarter-wave transformers. Isolation greater than 20 db was achieved over nearly an octave range (3.75 to 7.3 Gc), with insertion loss less than 0.5 db.

A. THEORETICAL AND MEASURED PERFORMANCE OF UNMATCHED BENDIX C-BAND CIRCULATOR

Continuing the preliminary work described in paragraph III-A of reference 1, the necessary modifications were made in the original program of the Recomp II digital computer (reference 2, paragraph III-A) to handle the extended frequency range and the negative values of μ_{eff}, for the corresponding normalized frequency range $0.283 < f' < 0.884$ ($1.56 < f < 4.86$ Gc). Values were calculated of the magnitudes of scattering matrix elements and the necessary matching impedance for ideal circulator performance (Figures 1 and 2). Two important observations can be made from these figures:

1. A tendency to circulate, exemplified by a ratio $|S_{13}|^2/|S_{12}|^2$ equal to 4.3 to 5.0 db, exists over this 3 to 1 frequency range.
2. The necessary matching impedance to make the circulator ideal over this range is approximately constant and real.

This general behavior has previously been observed experimentally with the Bendix circulator (for example, Figures 8 and 9 of reference 1), but the ratio of forward-to-reverse gain exhibited a peak in the middle of the band. It is believed that the different shape center conductor (paragraph III-A of reference 1) was responsible for this peak.

To eliminate a possible source of error between theory and experiments, measurements were made on the unmatched Bendix circulator (that is, with the dielectric rings removed) using a center conductor like Bosma's that just covered the ferrite disks. Separate photographs were made of the forward and reverse gain from 2 to 4 and 4 to 8 Gc. The essential gain data from these photographs, except for some minor wiggles, are shown combined in Figure 3.

Encouragingly, the measured curves of Figure 3 qualitatively resemble the theoretical $|S_{12}|^2$ and $|S_{13}|^2$ curves of Figure 1, except for the values of normalized frequency (f'). Consider the following comparison:

	f′ (Figure 3)	f′ (Figure 1)	f′ (Figure 3) / f′ (Figure 1)
Reverse gain valley	0.52	0.35	1.49
Forward and reverse gain peak	0.79	0.51	1.55
Forward and reverse gain valley	≈1.05	0.715	1.47
Forward and reverse gain = 0	1.335	0.884*	1.51

* Theoretically, when $f' = 0.884$, $\mu_{eff} = 0$. Thus, $|S_{12}|^2 = |S_{13}|^2 = 0$. Actually, as shown in Figure 1, the computer generated values of $|S_{11}|^2$, $|S_{12}|^2$, and $|S_{13}|^2$ for the case of $f' > 0.884$. These values are continuations of the old values for $f' < 0.884$, except that $|S_{12}|^2$ and $|S_{13}|^2$ were interchanged--which has been attributed to a sign error.

An approximate frequency-scale change of 1.5 to 1 would result in frequency coincidence of these salient features. In particular, consider the last. From equations 1, 2b, A-3, and A-9 of reference 1, and the relation $N_x/4\pi + N_y/4\pi + N_z/4\pi = 1$, $\mu_{eff} = 0$ when the normalized frequency is:

$$
\begin{aligned}
f' = m_o + h_o &= \frac{\gamma}{\omega_o}\left[H_1 + 4\pi M\right] \\
&\approx \frac{\gamma H_a}{2\omega_o}\left[\frac{3}{\left(\frac{N_z}{4\pi}\right)} - 1\right]
\end{aligned}
\qquad (1)
$$

Thus, a small change of $N_z/4\pi$, from the assumed value of 0.77 to 0.56, would shift the theoretical value of f' for $\mu_{eff} = 0$ from 0.884 to the observed 1.335. Considering the approximations made to calculate the demagnetization factors, such an error is quite possible. Thus, the theoretical and experimental results may agree better than would be indicated by a direct comparison of Figures 1 and 3.

Although Bosma's analysis perhaps fails to consider an optimally shaped center conductor for broad-band operation, the analysis predicts performance for the shape assumed that is in qualitative agreement with the measurements.

B. MEASUREMENTS ON STRIP-TRANSMISSION-LINE SLOTTED SECTION

The partially successful previous attempts at making a broad-band circulator by measuring a desired matching locus and then synthesizing a two-section quarter-wave transformer to approximate this locus (paragraph III-B of reference 1) depend on two assumptions that should be verified:

1. The strip transmission lines outside the ferrite region in the circulator as well as the transition to the coaxial connector have 50-ohm impedance.
2. Quarter-wave transformers constructed by using dielectric rings between the center conductor and the ground planes of the strip transmission line and varying the width of the center conductor according to the theory of Appendix D of reference 1 give an actual matching locus nearly identical with the theoretical locus.

A strip-transmission-line slotted section was constructed using the same ground-plane spacing, center-conductor dimensions,* and transition to a coaxial connector as in the Bendix C-band circulator. Measurements were first

---

* A slight reduction was made in center conductor width to give a theoretical line impedance of 50 ohms instead of 48.5 ohms calculated for the original Bendix circulator. This change had also been made in some of the attempts to apply the experimental matching technique.

made with a 50-ohm coaxial load with a measured SWR of less than 1.05 on a commercial coaxial slotted line. The results obtained, referred to a reference plane at the beginning of the transition, are shown plotted on an expanded Smith chart (Figure 4). The matched load is degraded appreciably by the transition; SWR varies from about 1.1 at the ends of the range to 1.18 in the middle. The slightly erratic order of experimental points is attributed to the difficulty of making the measurements.

Next, a simple matching section consisting of two halves of a dielectric ring was placed on both sides of the center conductor, filling the air spaces between the center conductor and ground planes at a distance of 0.38 cm from the transition. Values of $\epsilon = 4$ and $l = 0.558$ inch (Appendix B of reference 2) were chosen.

Figure 5 shows the resultant experimental locus of reflection coefficient referred to a reference plane at the edge of the dielectric furthest from the transition. It also shows the corresponding theoretical locus calculated as in Appendix II of reference 2 (assuming a perfect 50-ohm transition and strip transmission line). Although there is qualitative agreement, the quantitative agreement is poor between theoretical and experimental loci.

Detailed calculations on a Smith chart show that this discrepancy is mainly attributable to the imperfect transition (Figure 4) over the lower half of the frequency range. It is thought that discontinuities at the edges of the dielectric may be mainly responsible for the discrepancy over the upper half of the range.

C. EFFECTS OF CENTER-CONDUCTOR SHAPE

To facilitate the synthesis of the required matching network over a wide band, a study was made of the effect upon the matching locus of the shape of the center-conductor junction. Using the original Bendix circulator disks, matching loci for various center conductors were made and examined with regard to the following:

1. Closeness of the point groups,
2. Distance of the points from the $Z/Z_o = 1$ point

It is desirable to have the impedance points grouped tightly, and located as close as possible to the $Z/Z_o = 1$ point on the Smith chart in order to maximize the bandwidth over which synthesis by multi-section quarter-wave transformers is possible. It was observed that, for each center conductor, the tightness of the grouping of the points depends upon the applied static magnetic field and tends to improve as the field is increased. The field, however, was not allowed to exceed that value at which the forward loss at the lower end of the band (4 Gc) was observed to increase as a result of resonance absorption. For the disk used ($4\pi M_s$ = 1800 gauss), the optimum value of applied field was found to be 1150 gauss, and all plots were made at this field.

From loci similar to that in Figure 8 of reference 1, in which the points are grouped about a point on the real axis, it was surmised that the region in the ferrite may be represented under conditions of optimum grouping by a transmission line having an impedance Z. This impedance was less than 50 ohms in all cases observed. It was then reasoned that, if Z could be increased to 50 ohms, circulation could be obtained over a very wide band since it would not be limited by the matching network.

Thus, various junctions were constructed and tested that had thinner and narrower center conductors in the ferrite region. However, the results of these tests proved to be unsuccessful because although the points were generally closer to the origin, they were no longer closely grouped. Generally, the wider the center conductor, the more tight the grouping. The best results were obtained from the filleted center-conductor shown in Figure 6. A two-section matching transformer having the theoretical locus shown in Figure 6 was used to obtain the match. The results once again met with only moderate success for the reasons pointed out in Section B of this report.

D. MATCHING BY MEANS OF TUNING SCREWS

To obtain the desired match, it was decided to use tuning screws located along each arm of the circulator. Six screws were placed along each arm--three above and three below.

The screws were used in conjunction with the transformer and center conductor combination of Figure 6. Although the isolation could be increased over a small range, no significant improvement in performance characteristics could be obtained from this or any of the two-section quarter-wave transformers built thus far. Greater tunability was obtained with single-section transformers.

The results obtained from a 16-ohm transformer ($\epsilon = 10$) is shown in Figure 7. It can be seen that the isolation is greater than 20 db over close to an octave, and the insertion loss is less than 0.5 db. The applied magnetic field is 950 gauss, for which the impedance locus points are no longer bunched optimally. This condition was required to obtain the wide bandwidth over which isolation was greater than 20 db.

E. FUTURE PLANS

Attempts will be made to center the operating band of the circulator from its present 3.6 to 7.2 Gc octave band to the required 4 to 8 Gc band, and two final models of the octave-band circulator will be fabricated as required.

III. BROAD-BAND LOW-NOISE C-BAND AMPLIFIER

The purpose of this task was to: (1) develop a design theory for a low-noise solid-state amplifier suitable for use in C-band pulse-compression radars, and (2) design and construct a breadboard model for such an amplifier.

During this report period, work centered on double-tuning the balanced C-band parametric amplifier described in the previous report, so that the phase shift would be a linear function of the signal frequency. Qualitative study of idealized input impedance data provided the guidelines for this effort. The amplifier was double-tuned accordingly, giving about 10 db of gain and 500 Mc of bandwidth. The amplifier is packaged in a standard 19 by 24 inch rack mount, and is completely self-contained.

A. DOUBLE TUNING

1. GENERAL

To achieve a linear phase shift over a nominal 500-Mc bandwidth, it is necessary to multiple-tune the amplifier so that the phase is not overcompensated, as with a Butterworth filter. For the purpose of double tuning, the amplifier is viewed as a series-resonant circuit with a negative resistance. Figure 8 shows a Smith chart plot of an idealized amplifier input impedance and a series-resonant circuit for comparison. The major difference, of course, is the variation with frequency of the negative resistance of the amplifier.

To obtain a wider bandwidth, it is necessary to properly compensate for the impedance variation. A parallel resonant circuit can provide this compensation for a series circuit. The slope of the compensating circuit must be adjusted to yield the desired response. In this amplifier, an open circuited line, an integral number of half-wave-lengths long acted as the parallel resonant circuit. The slope of this circuit is given by

$$\frac{dY}{df} = j\,\frac{n\pi Y_o}{f_o}\,\frac{1}{\cos^2 n\pi \frac{f}{f_o}} \tag{2}$$

where

f_o = resonant frequency of the stub,

Y_o = characteristic admittance of the transmission line,

n = number of half wavelengths of the stub.

Thus, slope adjustment can be obtained by varying n and/or Y_o. Equation 2 points out the distributed property of the stub. At frequencies very near band center, where $\cos^2 n\pi\ f/f_o \approx 1$, the compensation is of the same nature as any parallel tank.

However, as the frequency deviates from midband, the slope increases because of the decrease of the $\cos^2$ function. This makes it possible to obtain compensation at the band edge, which would not be possible with a lumped L-C tank. Consequently, wider bandwidths than might be expected are attainable. It also makes it necessary to reach a compromise value of n and Y_o since too large a value of n would cause peaking on the skirts and too small a value of n would not give adequate slope compensation to obtain the required bandwidths; Y_o is used as a fine adjustment of the total compensation.

It is possible, then, to double-tune the amplifier at the diode terminals using an open-circuited stub of the correct length and impedance.

2. LINEAR PHASE RESPONSE

To investigate the direction in which the slope of the compensating circuit should be moved, we made use of an idealized input impedance plot obtained on the Recomb II digital computer and the expression developed in reference 1. An ideal transformer ($n = \sqrt{5}$) was assumed instead of a quarter-wave transformer to simplify the results (Figure 9). This network should give qualitative information about the comparison between double tuning for flat amplitude and double tuning for linear phase. The ideal amplifier input impedance plot (Figure 8) is the impedance looking into the transformer normalized to 50 ohms.

Converting this into admittance results in the first curve shown in Figure 10. Two final input admittance curves, after compensation, are also shown in this figure; the inside (30-ohms) curve being the result obtained when designing for flat amplitude. The middle curve (40 ohms) is obtained when the compensation is appropriately decreased and has very nearly linear phase. That this is the case may be seen in the phase plots of the two curves in Figure 11. Note that the phase angle of the maximally flat curve deviates on both sides of the average slope. The linear phase curve has a nearly flat slope.

The decrease of compensation required can be easily accomplished by increasing the characteristic impedance of the stub (equation 2). The amplitude response that corresponds to a flat phase is much more rounded than the flat amplitude response. Comparative amplitudes are shown in Figure 12. When double tuning for linear phase, it is expedient to look for this characteristic amplitude response rather than attempt to do fine tuning using the more difficult phase measurement.

B. AMPLIFIER PERFORMANCE

The amplifier was double-tuned to give the rounded response curve associated with the linear phase characteristic. The stub impedance required was about 18 ohms. To obtain a flat amplitude, a lower impedance (about 15 to 16 ohms) would be required.

Photographs of the amplifier pass band are shown in Figure 13. The characteristics of the amplifier are:

Gain	9.8 db
Bandwidth	500 Mc
Noise factor	3.55 db

A point-by-point plot of the gain characteristic is shown in Figure 14. The amplifier has an extremely smooth amplitude response, which is a vital requirement for phase linearity.

C. MEASUREMENT OF PHASE SHIFT

The phase was measured using a bridge setup similar to that reported in reference 1. The deviation from phase linearity of the amplifier was measured, and is shown in Figure 14 together with the amplifier amplitude characteristic. Residual SWR's in the cables and attenuators are believed to cause the peaks and valleys in the phase curve. The actual amplifier phase characteristic would be as shown by the dotted line in Figure 14.

D. AMPLIFIER PACKAGE

The amplifier was packaged in a standard 19 by 24 inch rack mount. Figure 15 shows two views of the completed amplifier assembly. A standard AIL klystron power supply was used to operate the klystron. Provisions have been made on the front panel for monitoring the beam and reflector voltage, and the diode bias voltage. The diode current may be monitored by connecting a microammeter between the DIODE CURRENT and DIODE BIAS test points.

E. FUTURE PLANS

During the next report, the measurement technique will be refined to eliminate phase errors.

IV. REFERENCES

1. S. Hamilton, W. W. Heinz, S. Okwit, E. W. Sard, and K. Siegel, "Third Quarterly Progress Report on Solid-State Circuits," Report No. 1654-I-3, AIL, Deer Park, New York, January 1963.

2. S. Hamilton, W. W. Heinz, S. Okwit, E. W. Sard, and K. Siegel, "Second Quarterly Progress Report on Solid-State Circuits," Report No. 1654-I-2, AIL, Deer Park, New York, October 1962.

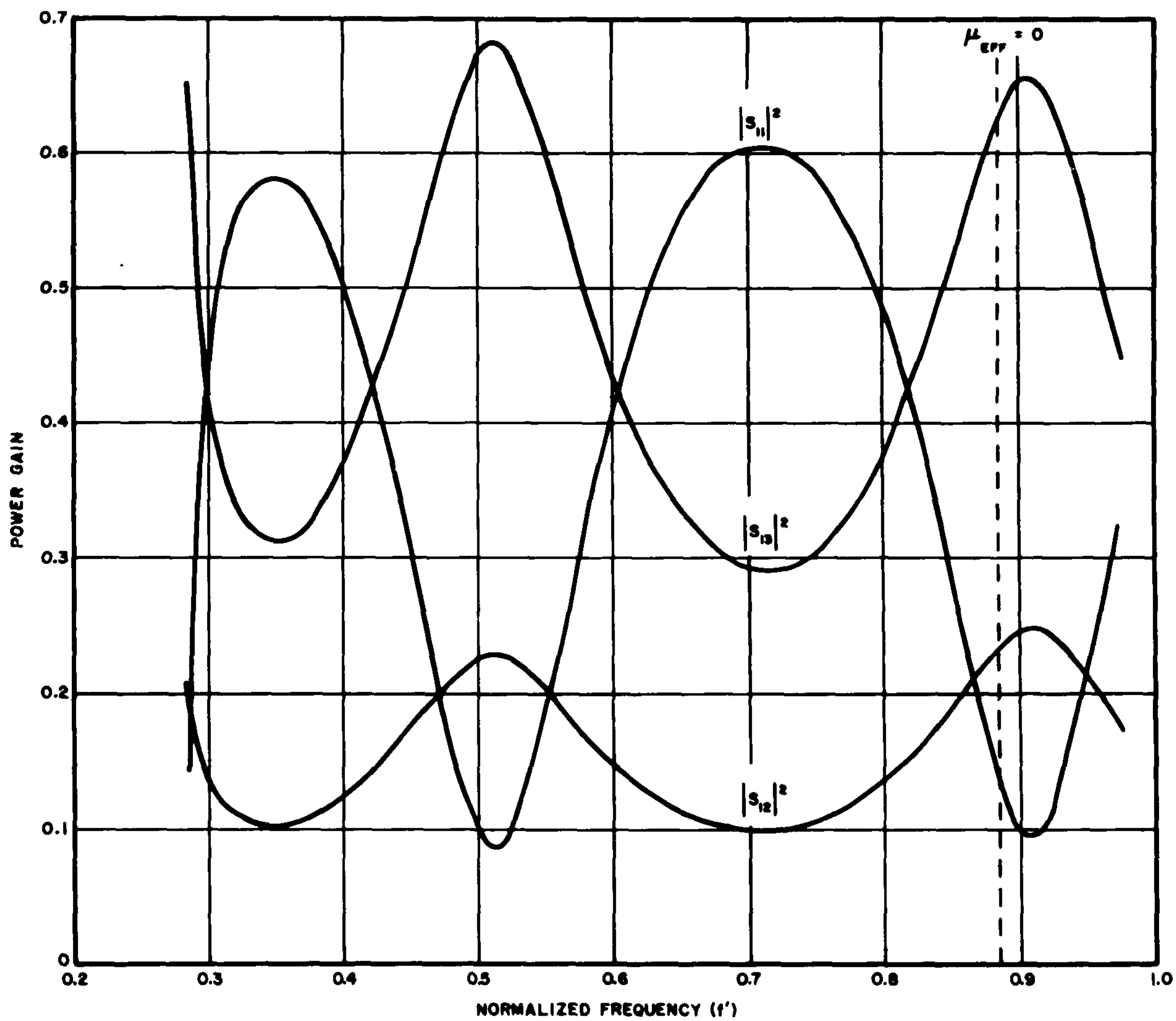


FIGURE 1. THEORETICAL POWER GAIN OF UNMATCHED BENDIX CIRCULATOR WITH CENTER CONDUCTOR PER BOSMA

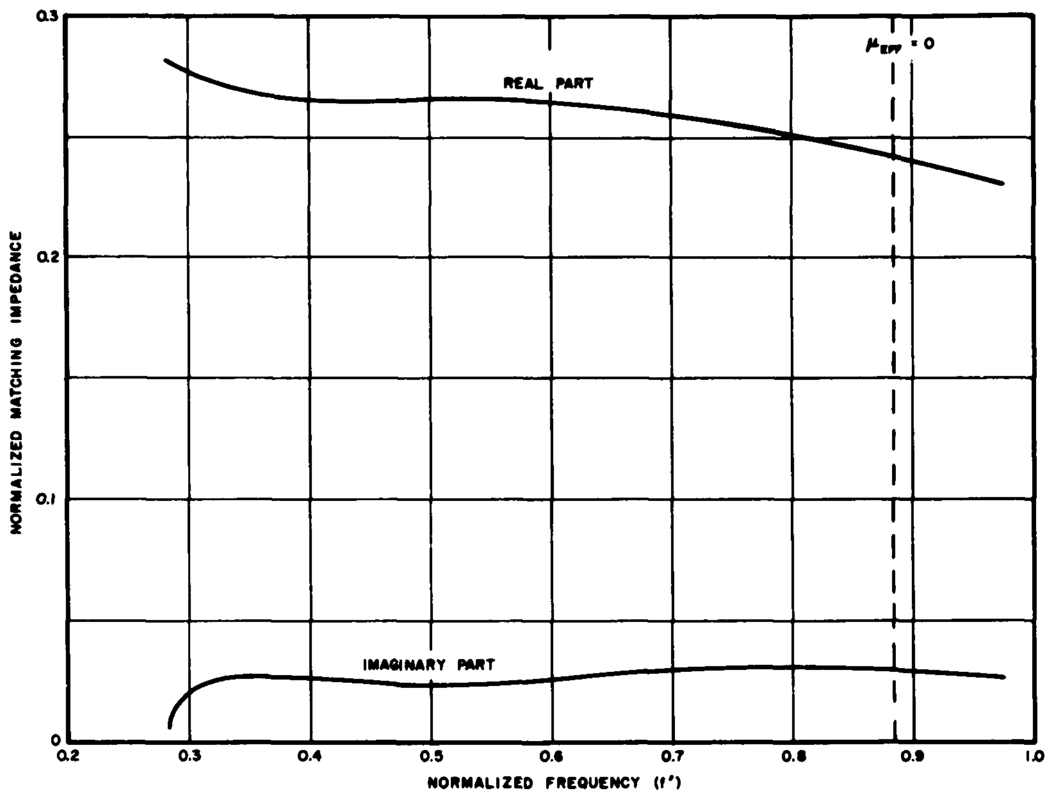


FIGURE 2. THEORETICAL MATCHING IMPEDANCE FOR UNMATCHED BENDIX CIRCULATOR WITH CENTER CONDUCTOR PER BOSMA

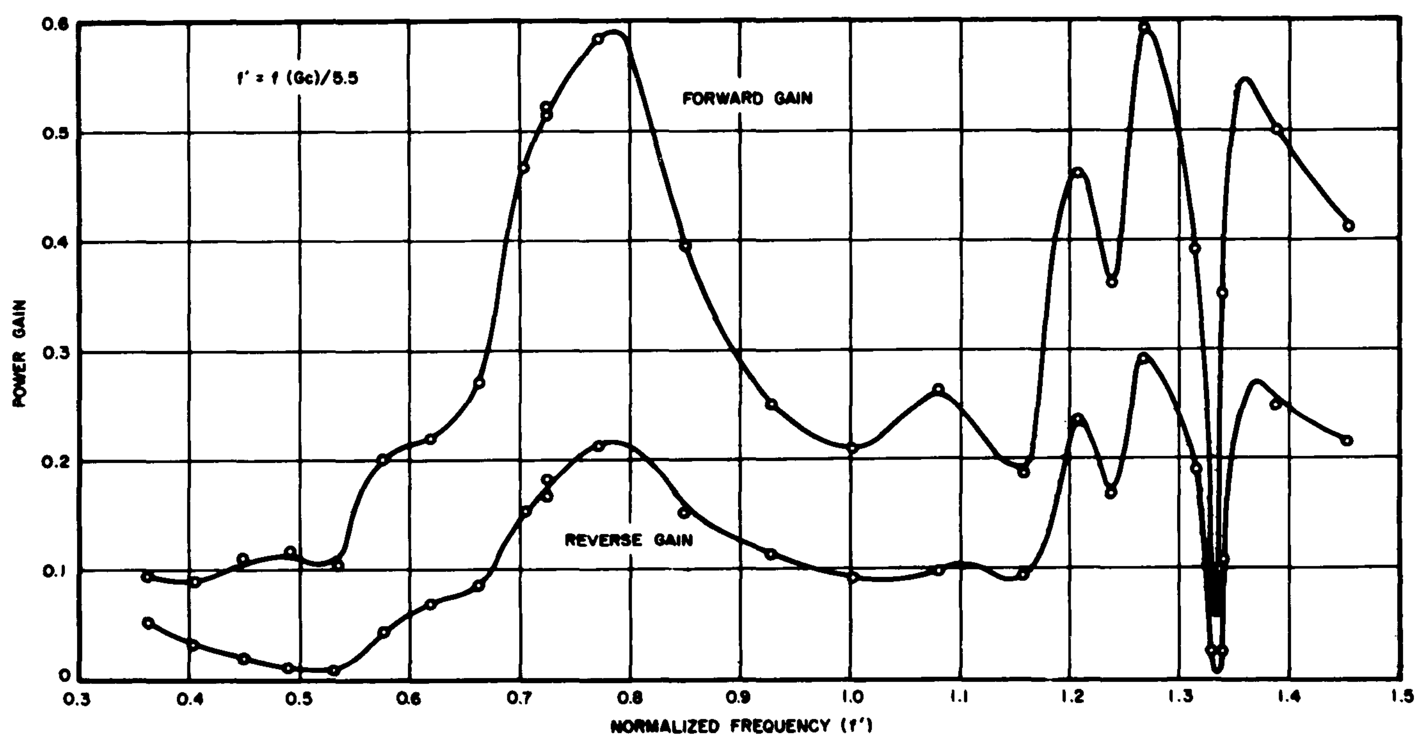
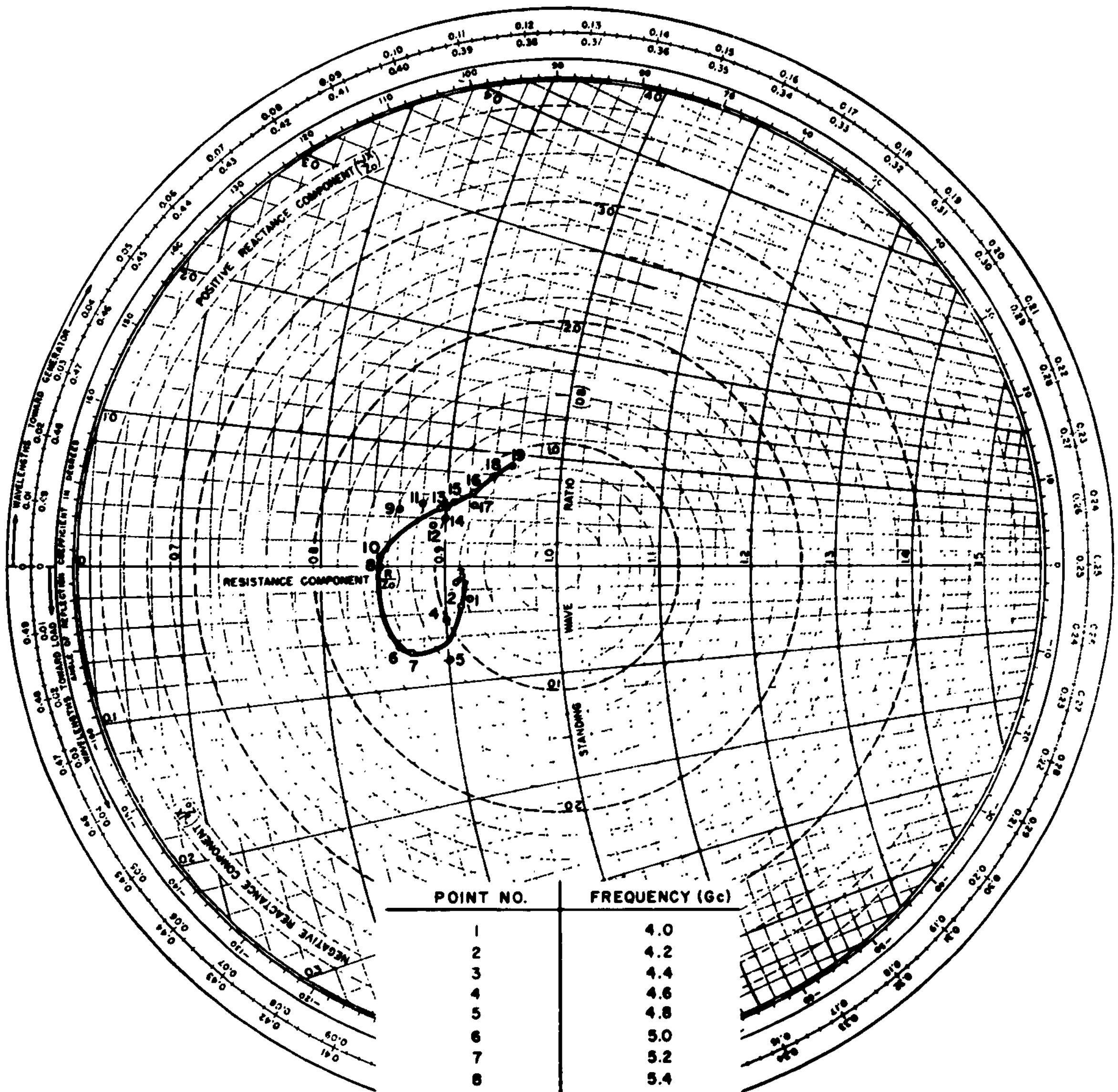
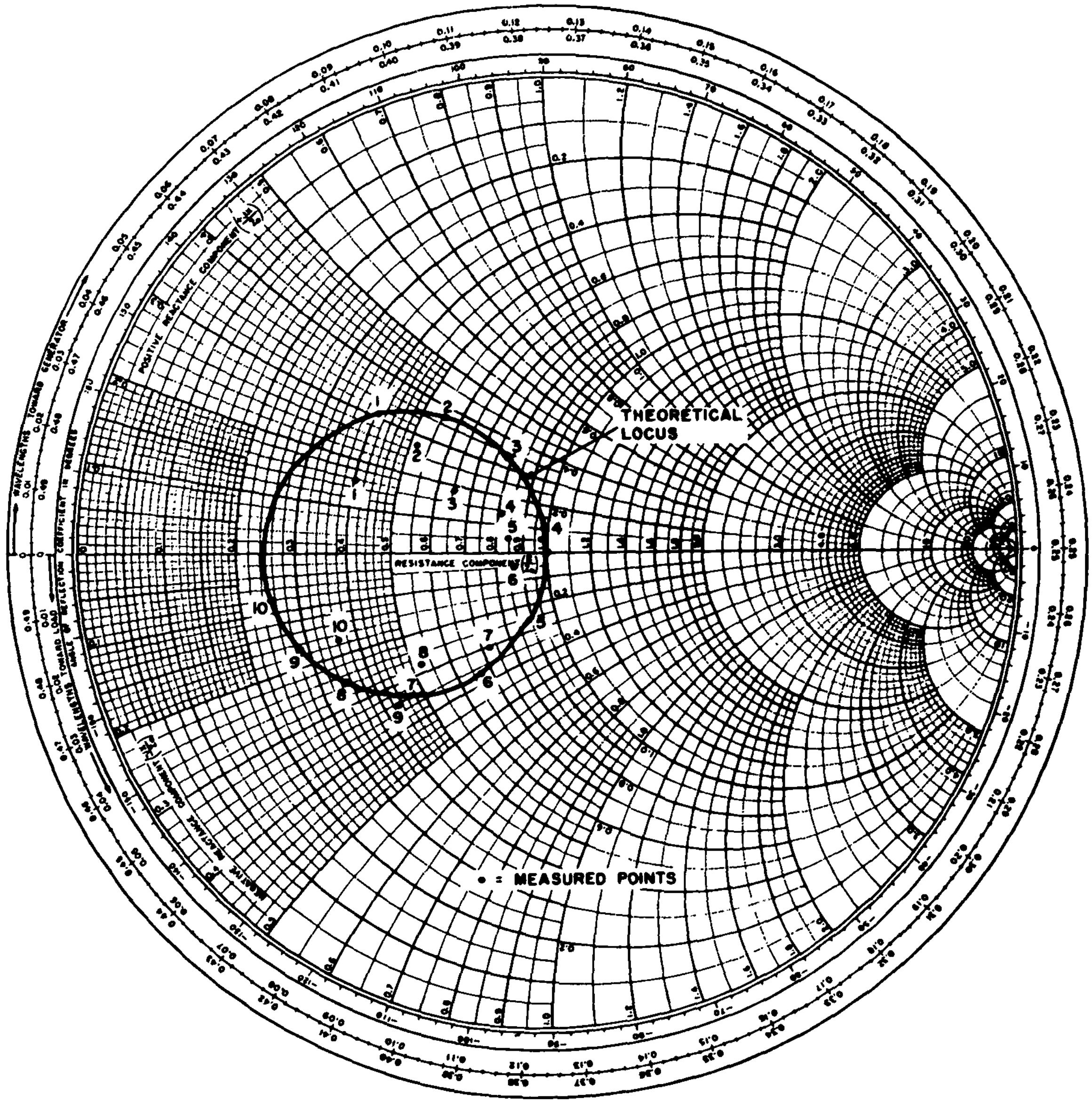


FIGURE 3. MEASURED POWER GAIN OF UNMATCHED BENDIX CIRCULATOR WITH CENTER CONDUCTOR PER BOSMA



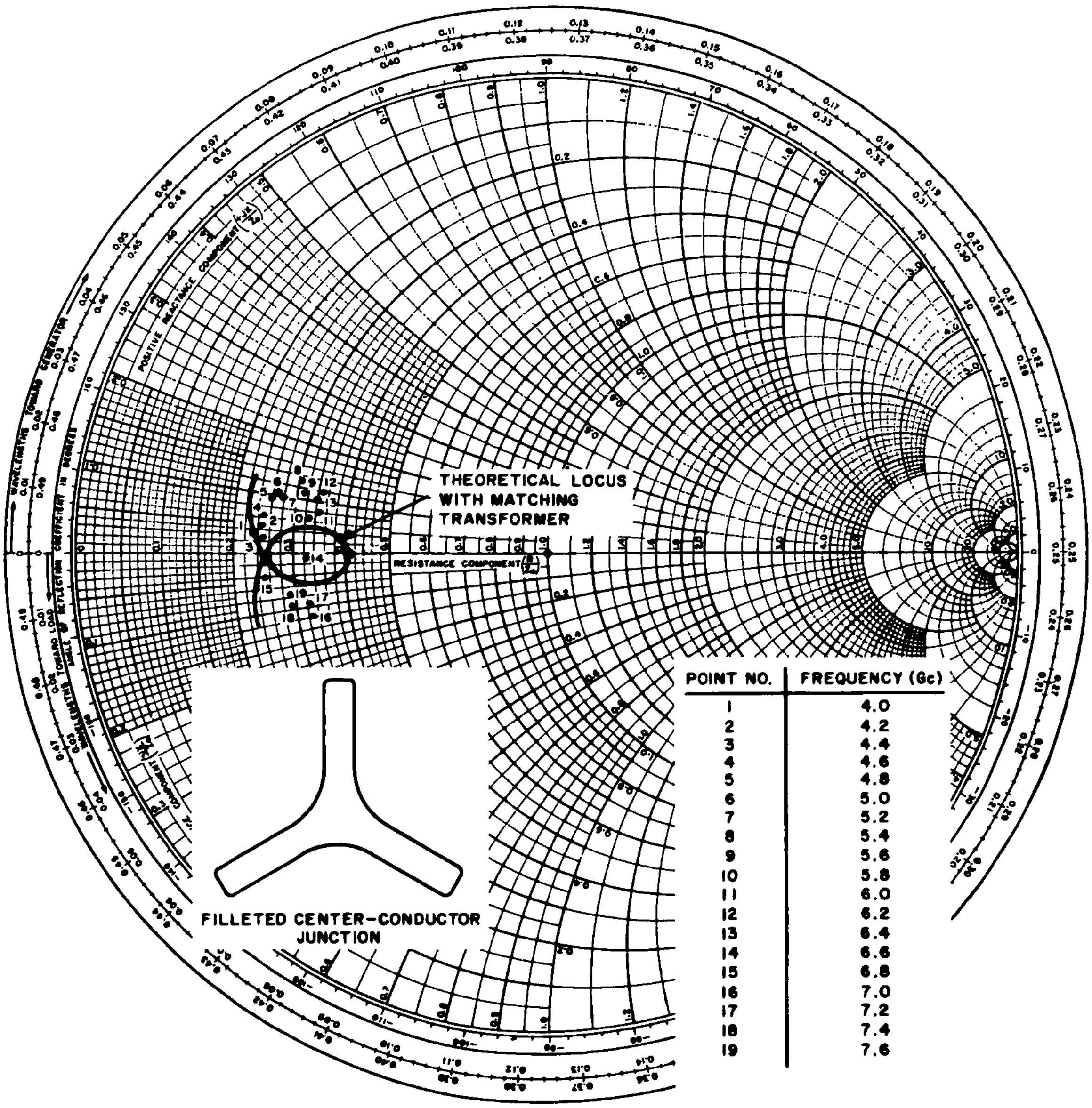
POINT NO.	FREQUENCY (Gc)
1	4.0
2	4.2
3	4.4
4	4.6
5	4.8
6	5.0
7	5.2
8	5.4
9	5.6
10	5.8
11	6.0
12	6.2
13	6.4
14	6.6
15	6.8
16	7.0
17	7.2
18	7.4
19	7.6

FIGURE 4. IMPEDANCE PLOT OF TRANSITION BETWEEN STRIP TRANSMISSION LINE AND COAXIAL LINE



POINT NO.	FREQUENCY (Gc)
1	4.0
2	4.4
3	4.8
4	5.2
5	5.6
6	6.0
7	6.4
8	6.8
9	7.2
10	7.6

FIGURE 5. REFLECTION COEFFICIENT OF STRIP TRANSMISSION LINE WITH DIELECTRIC RING HALVES



POINT NO.	FREQUENCY (Gc)
1	4.0
2	4.2
3	4.4
4	4.6
5	4.8
6	5.0
7	5.2
8	5.4
9	5.6
10	5.8
11	6.0
12	6.2
13	6.4
14	6.6
15	6.8
16	7.0
17	7.2
18	7.4
19	7.6

FIGURE 6. POINTS TO BE MATCHED FOR FILLETED CENTER CONDUCTOR AND THEORETICAL MATCHING LOCUS

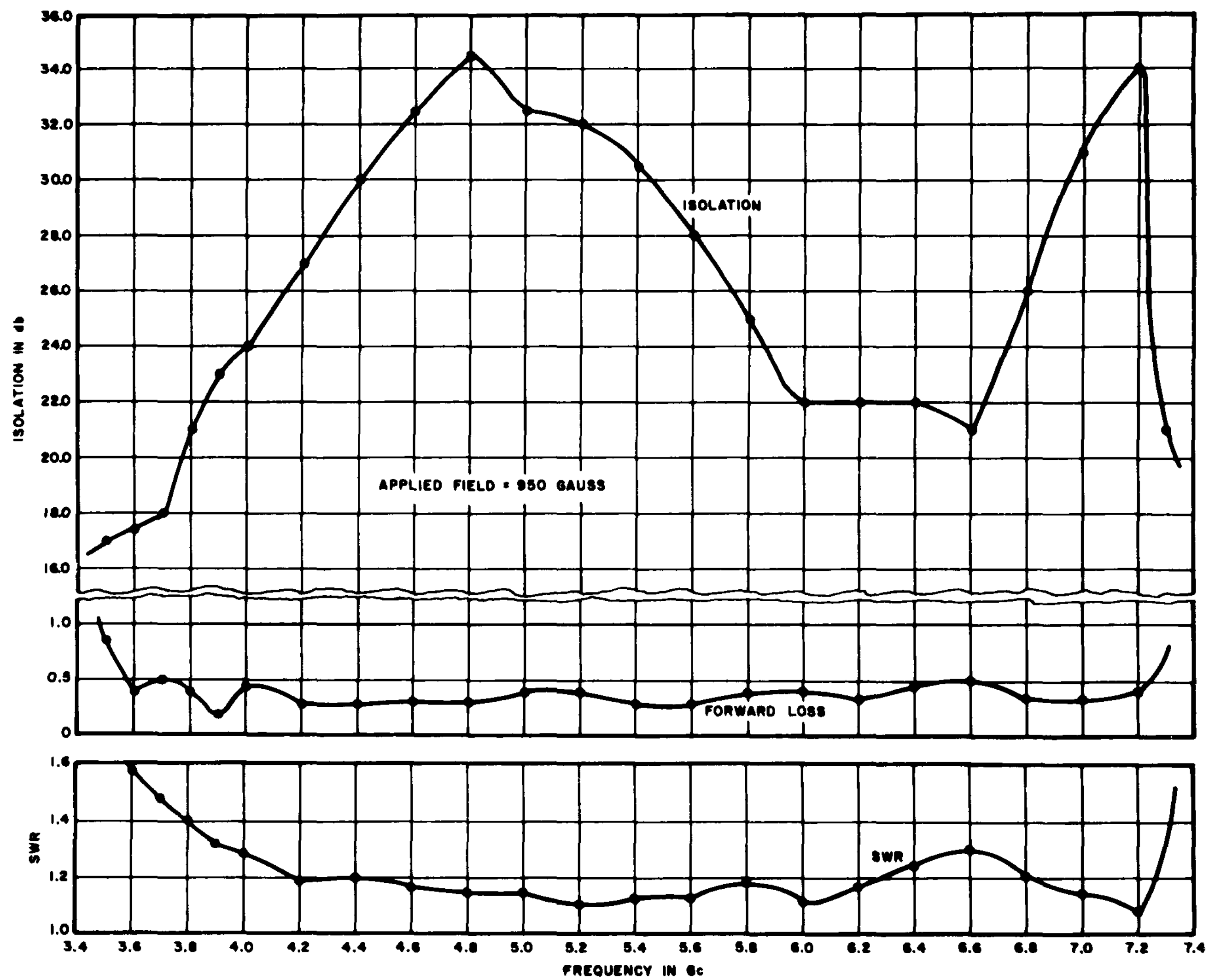


FIGURE 7. CHARACTERISTICS OF CIRCULATOR USING TUNING SCREWS AND SINGLE-SECTION QUARTER-WAVE TRANSFORMER

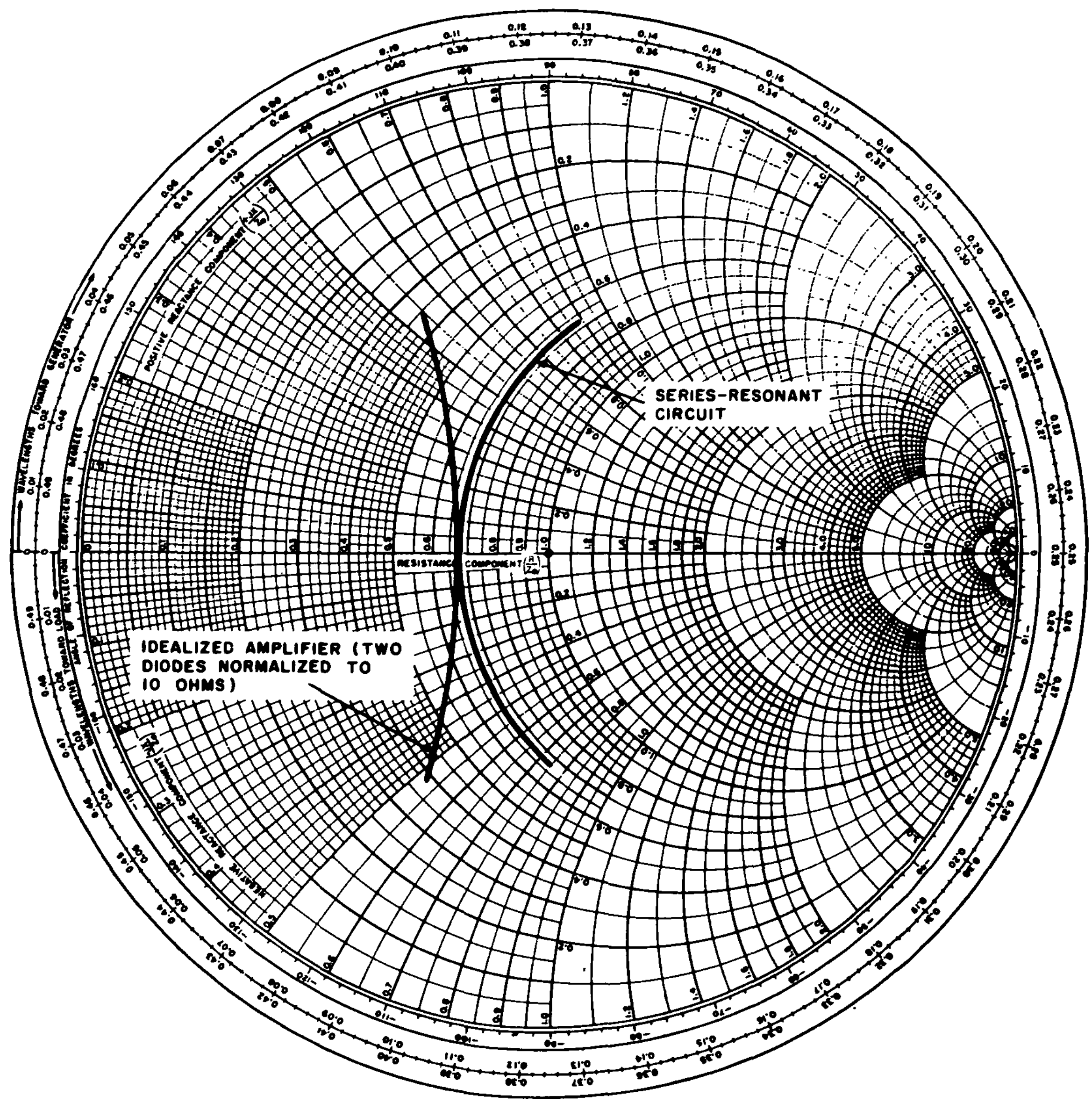


FIGURE 8. SMITH CHART PLOT OF IDEALIZED AMPLIFIER AND SERIES-RESONANT CIRCUIT

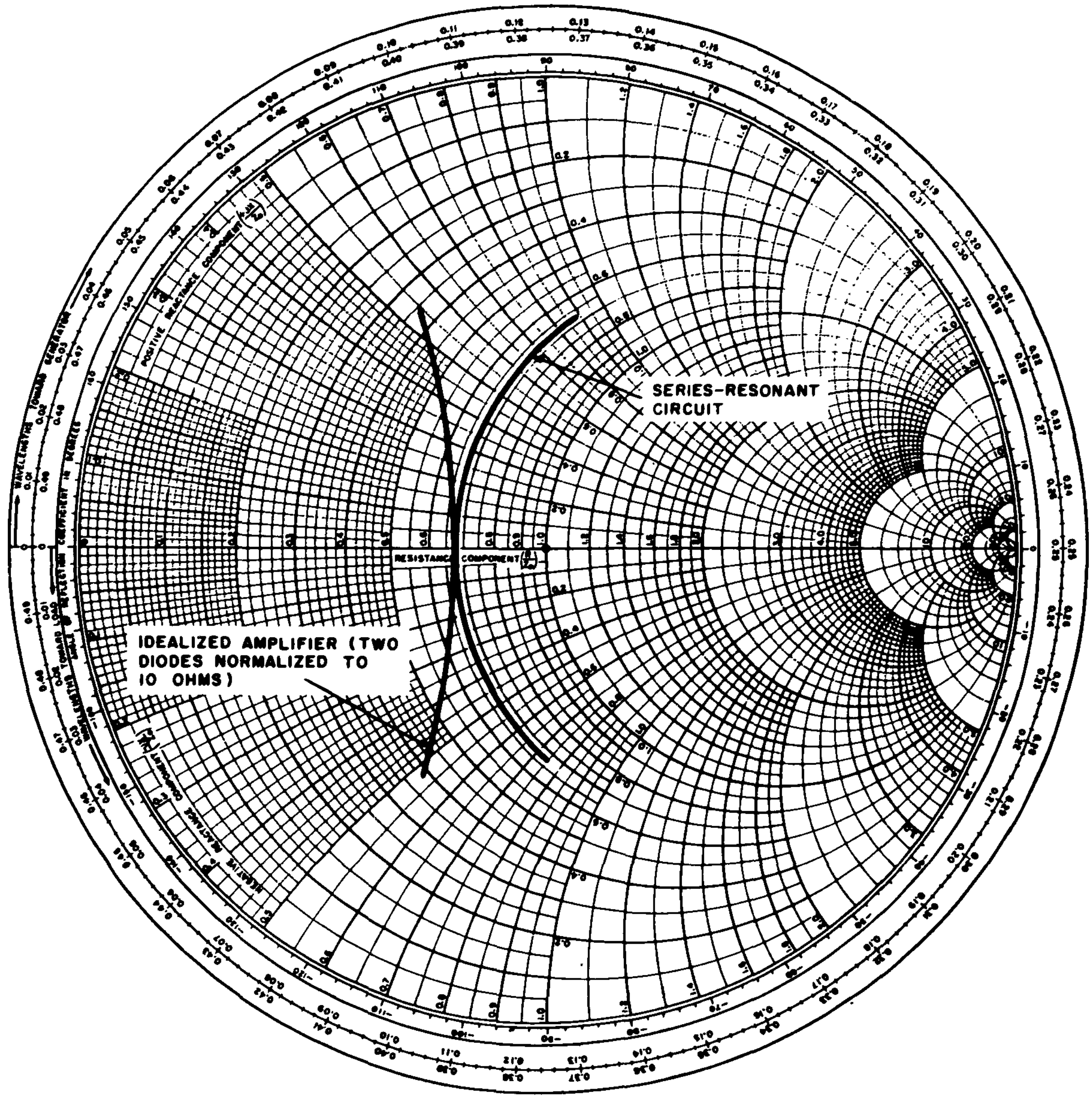


FIGURE 8. SMITH CHART PLOT OF IDEALIZED AMPLIFIER AND SERIES-RESONANT CIRCUIT

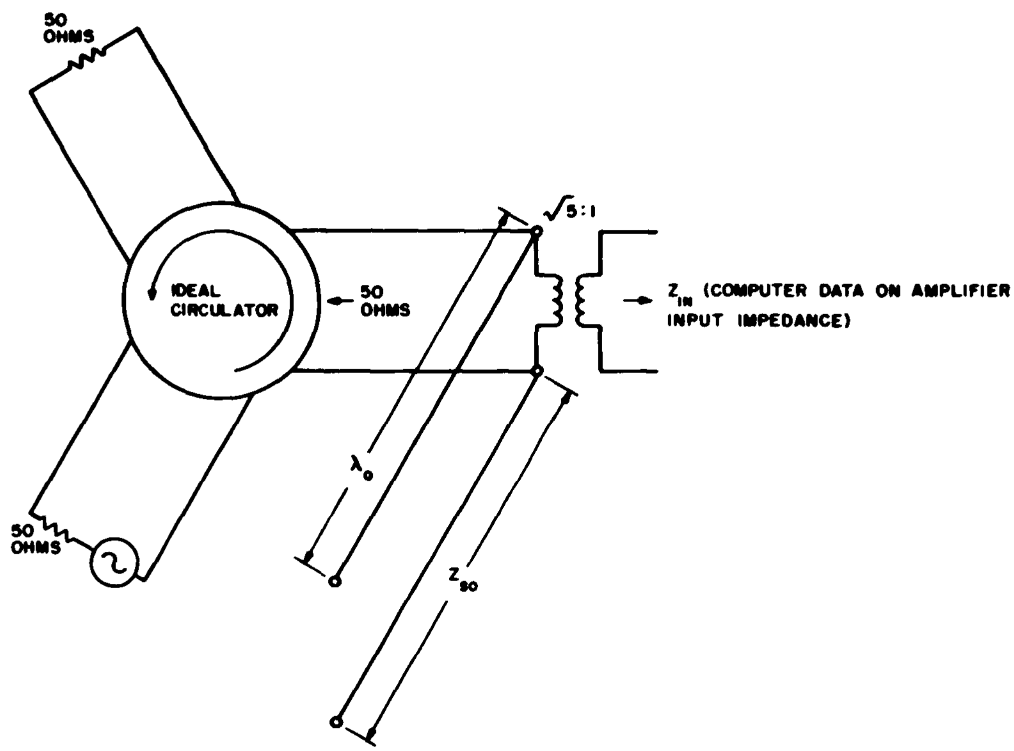


FIGURE 9. NETWORK USED IN COMPARING LINEAR-PHASE DOUBLE TUNING AND FLAT AMPLITUDE

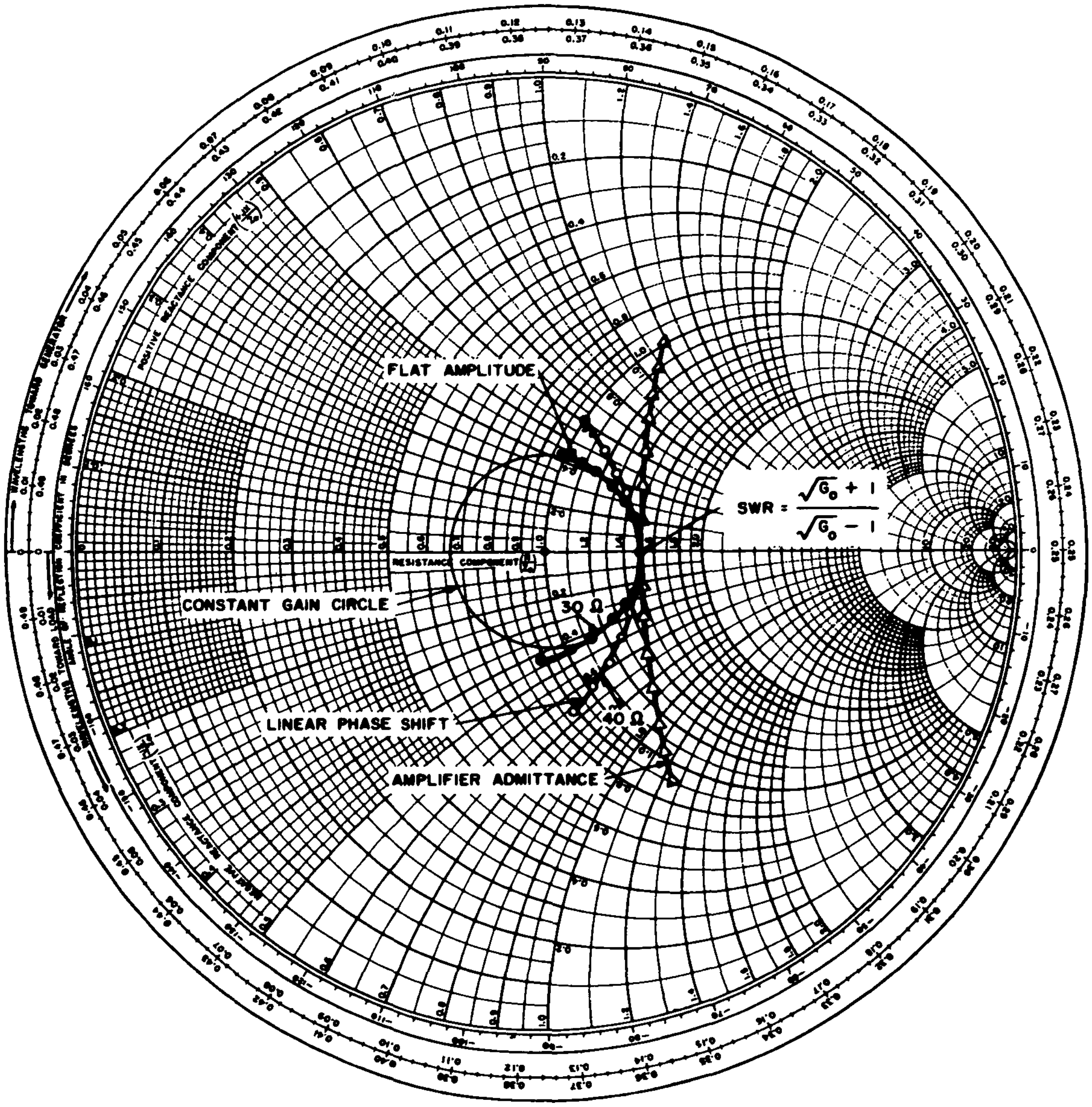


FIGURE 10. SMITH CHART PLOT OF LINEAR PHASE RESPONSE

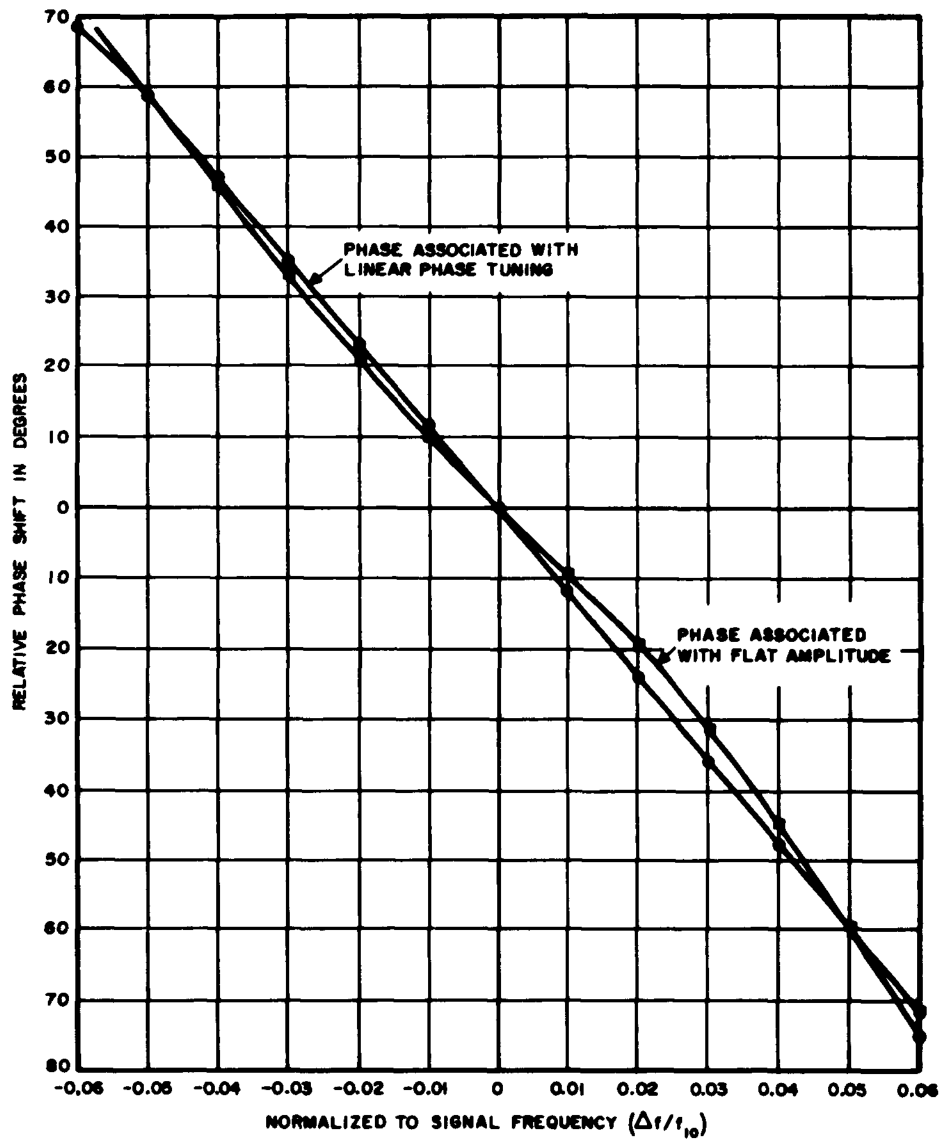


FIGURE 11. PLOT OF PHASE SHIFT VS NORMALIZED TO SIGNAL FREQUENCY

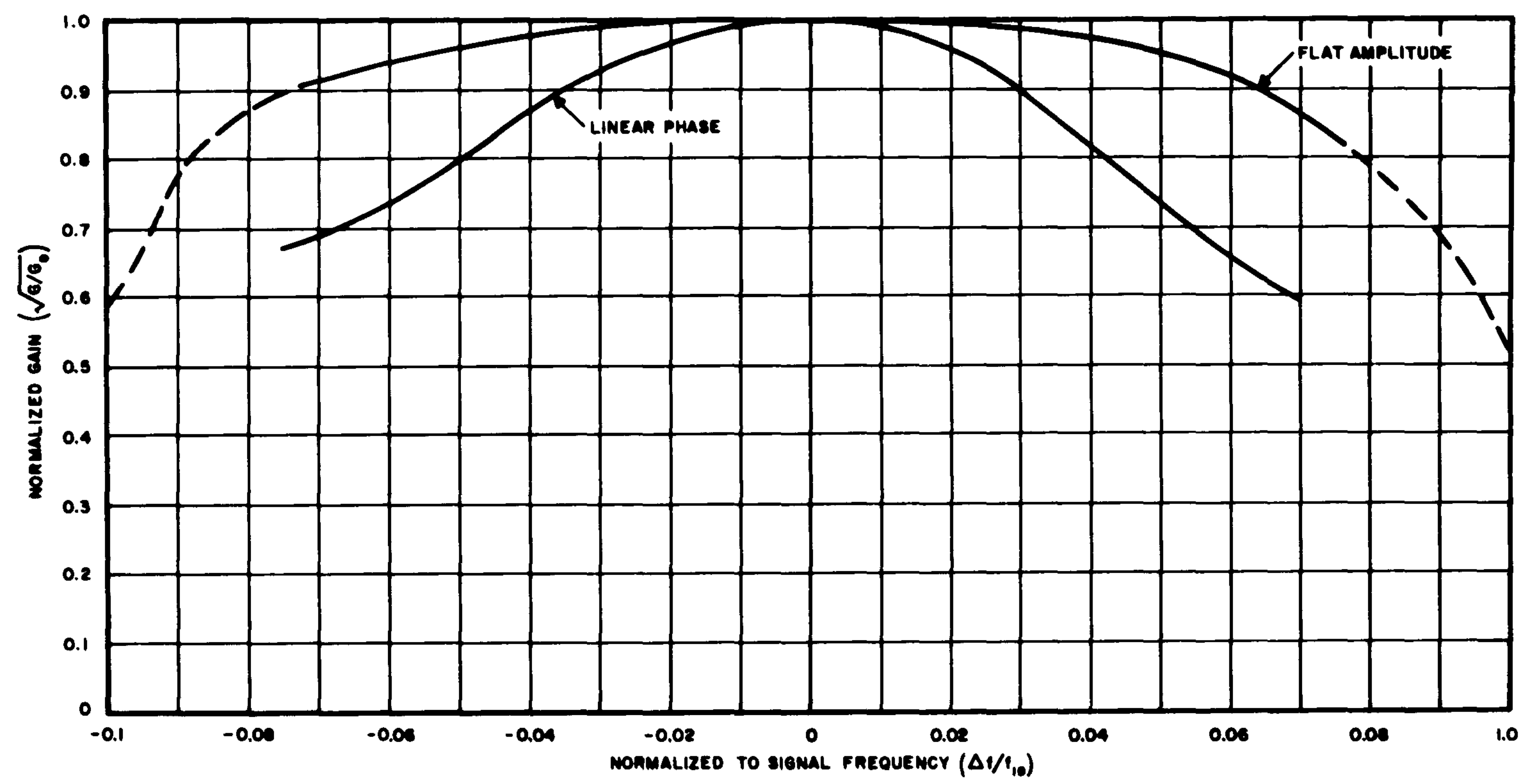


FIGURE 12. PLOT OF NORMALIZED GAIN VS NORMALIZED SIGNAL FREQUENCY

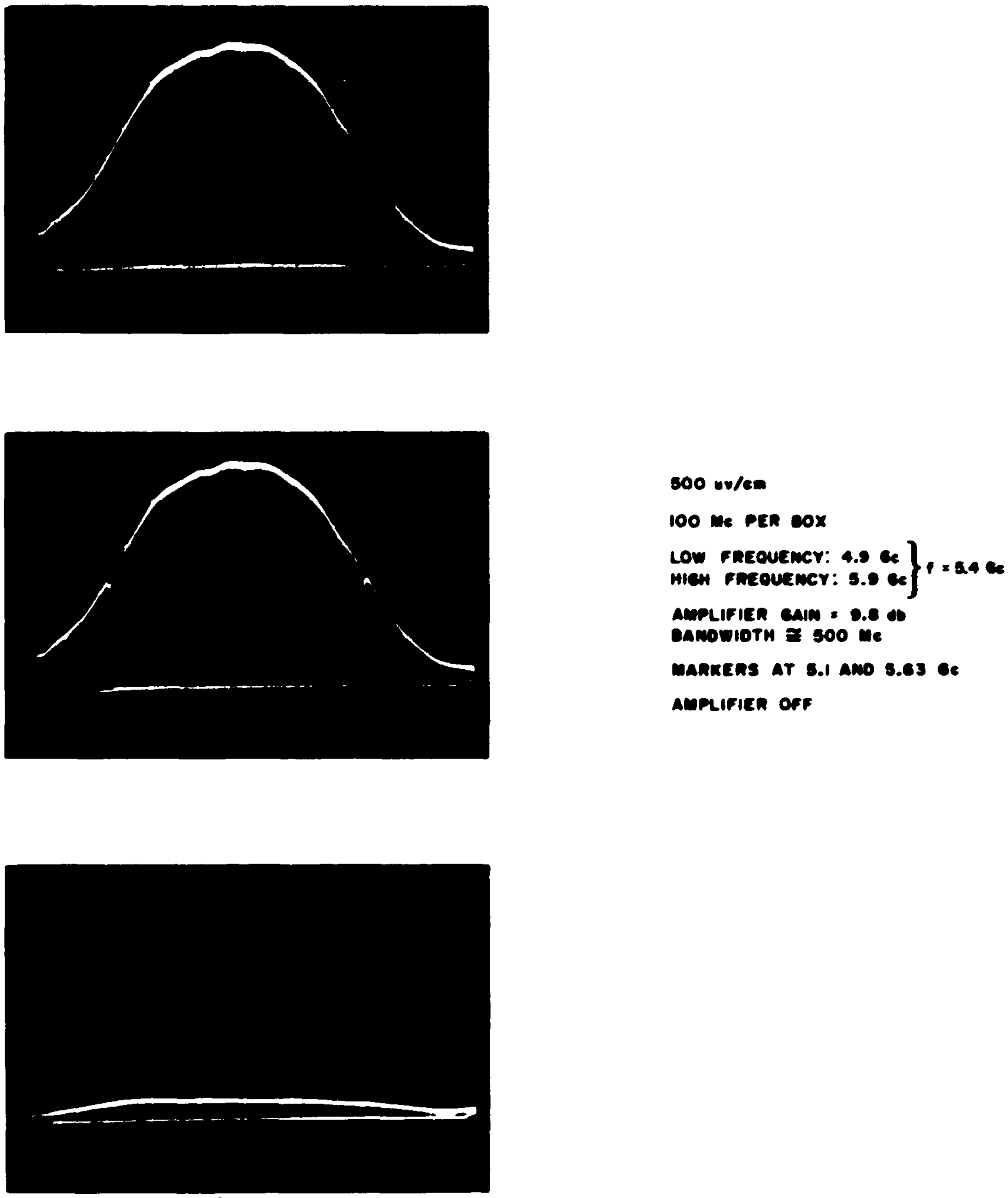


FIGURE 13. AMPLITUDE CHARACTERISTIC OF C-BAND PARAMETRIC AMPLIFIER

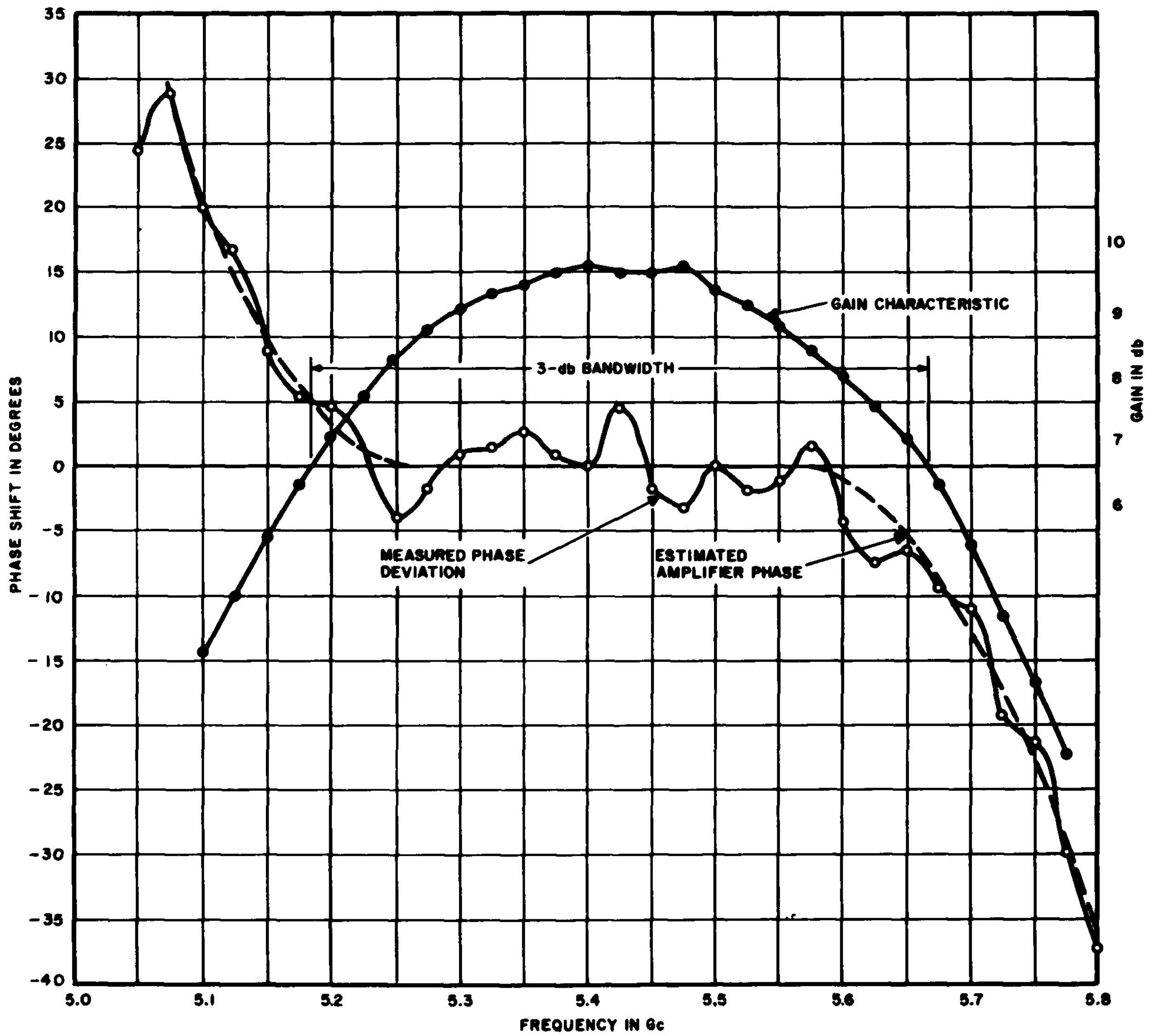
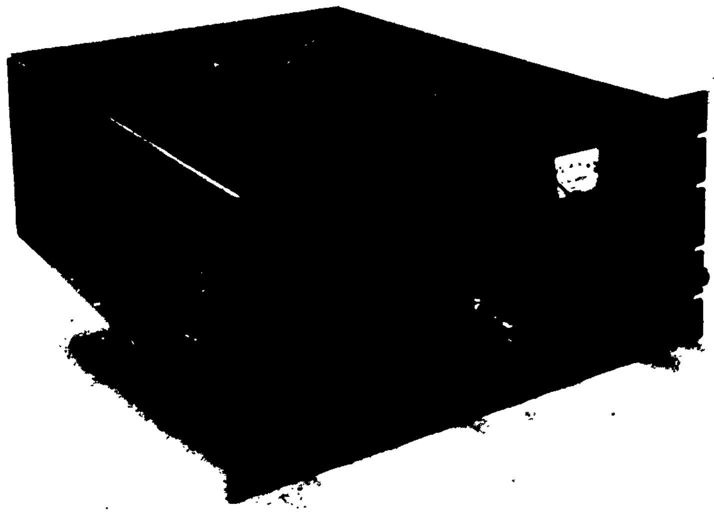
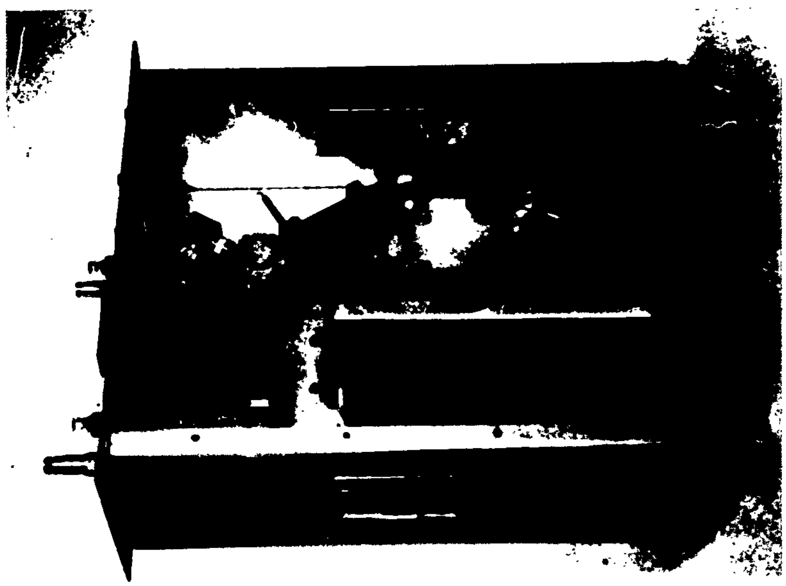


FIGURE 14. DEVIATION FROM LINEARITY OF PHASE SHIFT OF C-BAND PARAMETRIC AMPLIFIER



A. FRONT PANEL



B. INTERNAL VIEW

FIGURE 15. COMPLETED AMPLIFIER ASSEMBLY

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